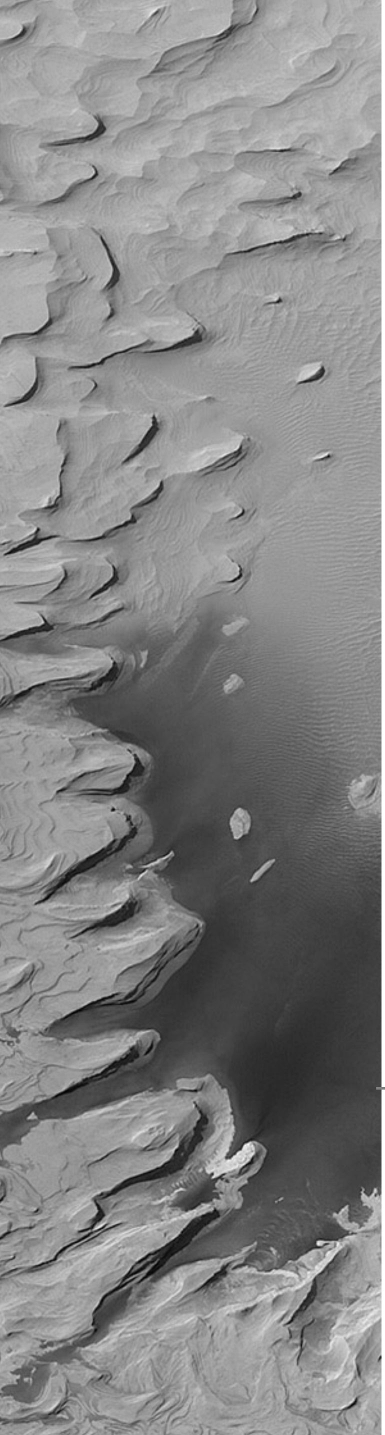

ICAR'05 Workshop on Navigation and Manipulation for Mars Rovers

Approach and Instrument Placement Validation

Won S. Kim
Jet Propulsion Laboratory
California Institute of Technology
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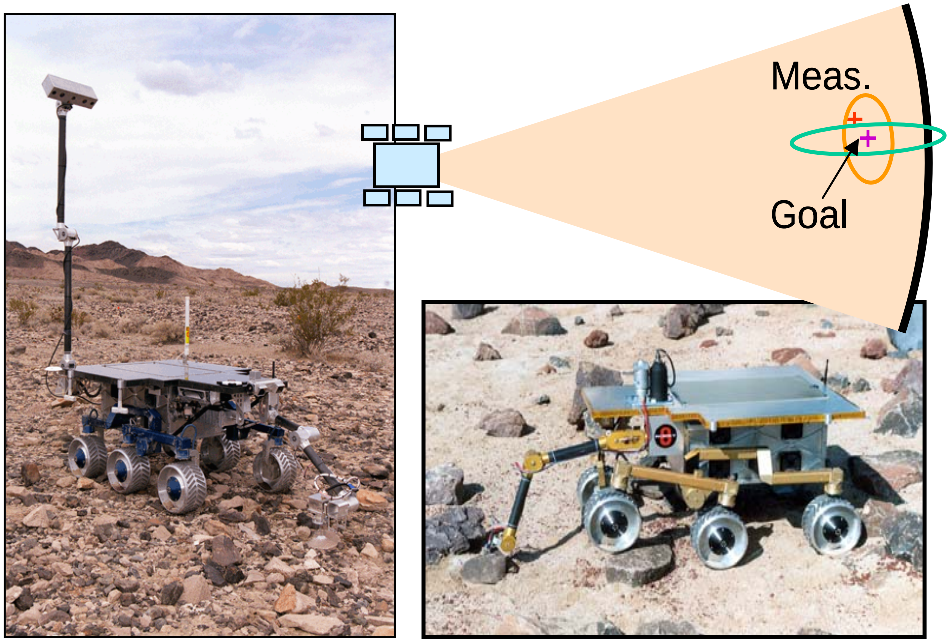
(818)354-5047
Won.S.Kim@jpl.nasa.gov

Approach and Instrument Placement Validation

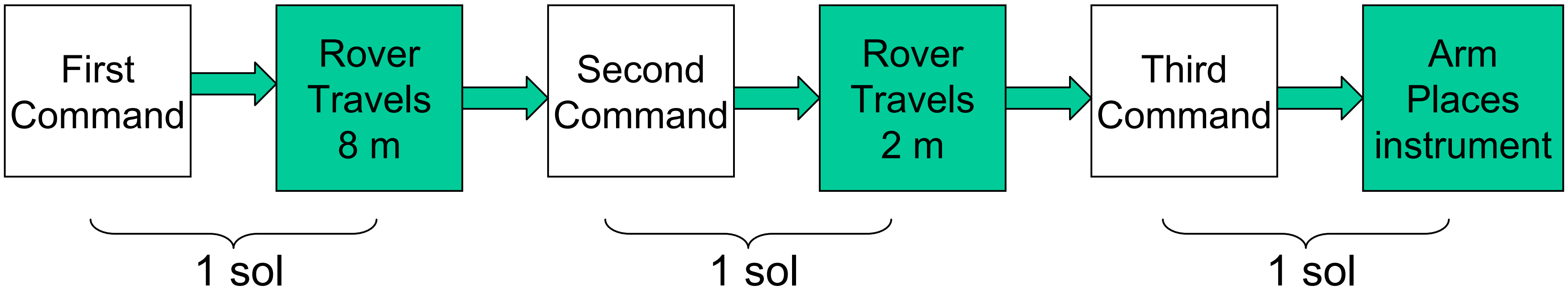
Objectives:

- Provide an experimentally validated single-sol instrument placement capability to MSL, where the science target is up to 10 m away (background: MER takes minimum 3 sols)
- Provide technology providers with early feedback for improvements

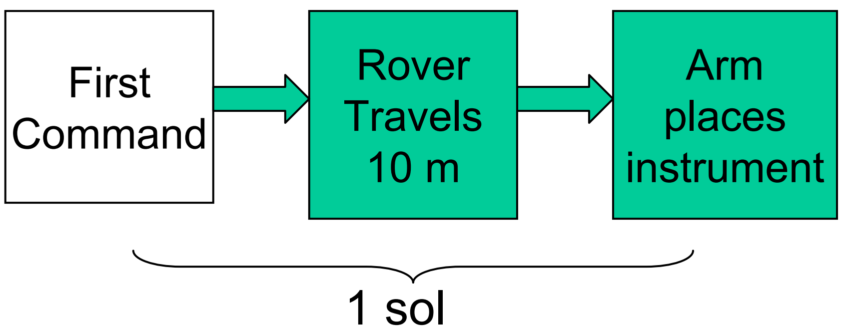


Problem Statement: State of Art

- **MER Baseline: 3-sol instrument placement from 10 m away**



- **MSL Enhancement: 1-sol instrument placement from 10m away**



- **20% to 25% increase in science return**
  – 8 to 10 sols/rock will be reduced to 6 to 8 sols/rock

Single-Sol Instrument Placement Technologies

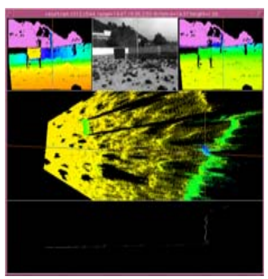
Mast cam. panoramic imagery → **Ground operator/ scientist Target Selection** → 10m → **Target Tracking during Approach** → Arm's reach → **Stereo Vision** → Range map → **Manipulation to place instrument**

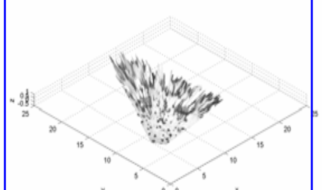
Validate: Stereo vision

Camera calibration

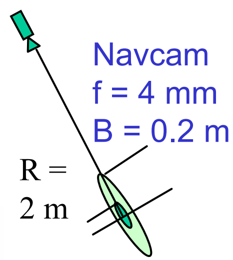
Metrology

Stereo range map



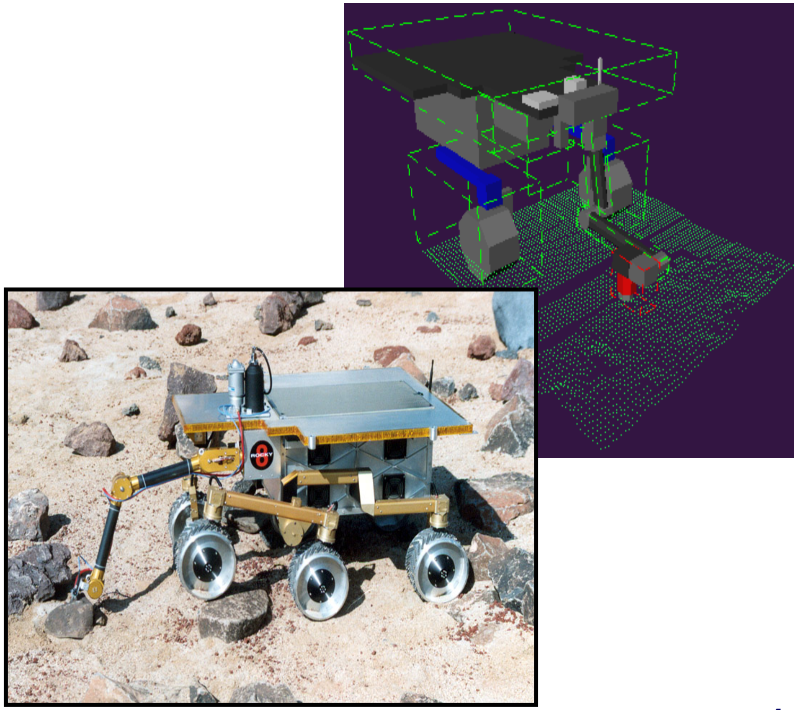


Stereo range error



$\sigma_{\Delta R}$ = 7.2 mm

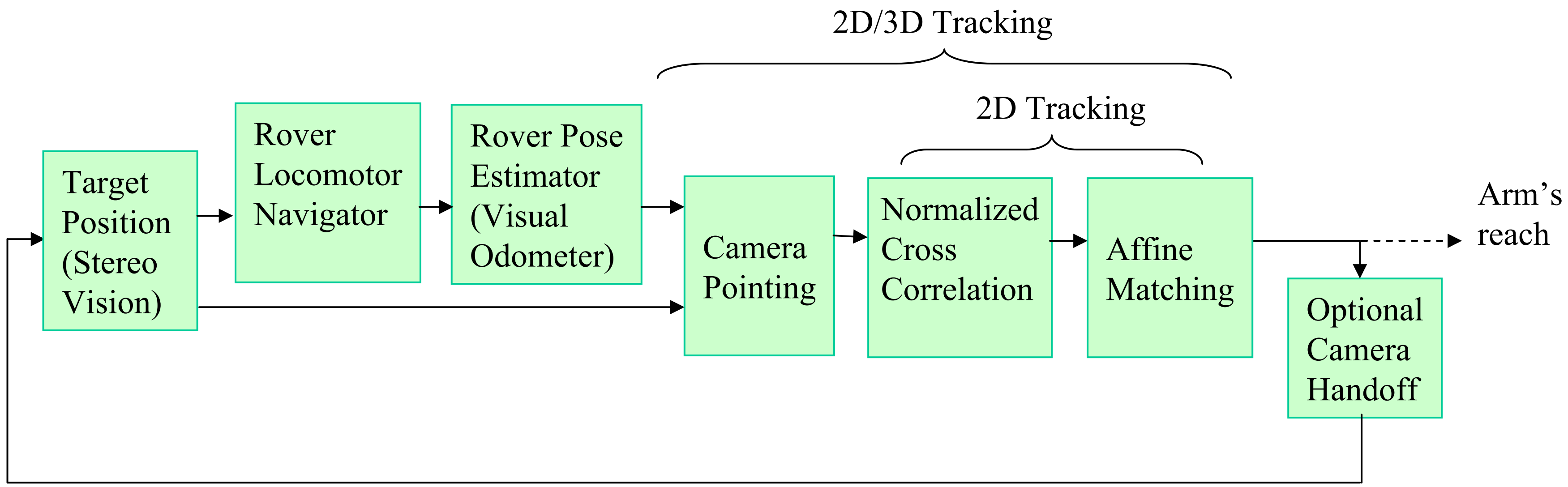
Validate: Manipulation



Technical Approach / System Description

- **Validation approach**
  - Component-level white-box validation
  - Provide technology providers with feedback for improvements and bug fixes

- **2D/3D visual tracker system for target approach**



Navcam Tracking Example – good target with good lighting

9.6m

7.3m

4.7m

2.1m

Pancam Tracking Example – Good Target with Good Lighting

9.6m

7.2m

4.6m

2.8m

Pancam Tracking Example – Good Target with Good Lighting

Movie

Pancam Tracking Example – Bad Target with Background Change

10.8m

10.3m

9.9m

9.3m

Navcam/Pancam Tracking Examples – Lighting/Reflection/Shadow Change

Nav 9.7m

Nav 9.2m

Pan 8.7m

Pan 3.5m

Computing Target Approach Accuracy

- Without visual target tracking
  - 3σ approach error = 22.2 cm using Pancam and visual odometry (2% error)

$$\Delta R_{no\_tracking,10m} = \sqrt{\Delta R_{stereo,10m}{}^2 + \Delta R_{nav,10m}{}^2}$$

- With visual target tracking
  - 3σ approach error = 1.5 cm at R= 1 m distance using Pancam initially with subsequent camera handoffs to Navcam and Hazcam

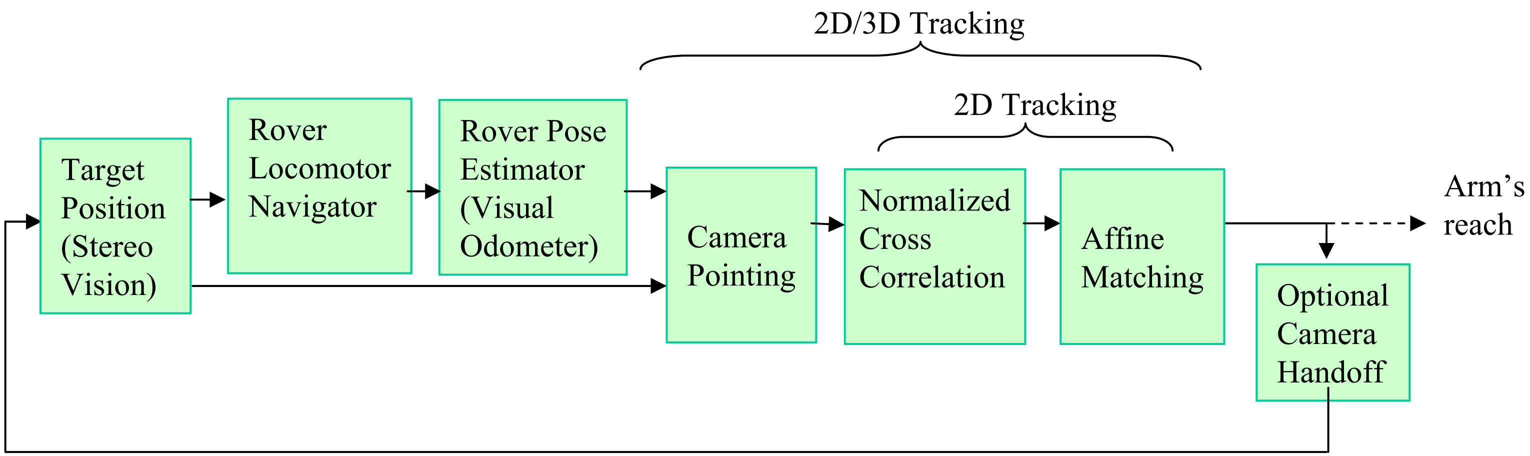
$$\Delta R = \frac{R^2}{f_{s2} B_2} (\Delta d \frac{f_{s2}}{f_{s1}}) = \frac{R^2}{f_{s1} B_2} \Delta d$$

Focal length (1/3" CCD camera)	Field of view angles	Stereo baseline	Stereo range error (3σ) at 10 m distance	Target approach error (3σ) with 2% navigation error	Target approach error (3σ) with ideal visual tracking and camera handoff
16 mm	17° × 13°	30 cm	9.7 cm	22.2 cm	1.5 cm
6 mm	49° × 37°	20 cm	38.8 cm	43.7 cm	3.9 cm
2.3 mm	113° × 86°	10 cm	202.2 cm	203.2 cm	10.1 cm

Test Plan for 2D/3D Tracker

Jet Propulsion Laboratory

2D/3D Visual Target Tracker System



Validation Method

- Error Budget Model based on component-level white-box approach
- Experimental Test Variables (rover motion step size; straight flat, rocky, or winding path; high-texture or low-texture targets; lighting conditions; software algorithms, configuration, parameter settings)
- Tracking performance metrics (tracking success percentage and tracking error)

Tracking Reliability and Error Budget Model

Rover locomotion/navigator	Rover motion changes the target image, affecting the matching performance: • Target image size change • Target image roll, pitch, yaw changes
Rover pose estimator using visual odometer (VO)	VO estimation error affects active camera control: • Rover pose distance error • Rover pose orientation error
Target position estimation using stereo vision	Stereo vision triangulation error affects active camera control: • Target position error on image plane
Active camera control to point the fixed-mast to the target (for Pancam and Navcam only)	Fixed-mast pointing errors: • pan/tilt encoder resolution • pan/tilt backlash • mast calibration accuracy
2-D target tracking using normalized cross-correlation, scale, and affine matching	The above active camera control with VO and stereo vision determines the target image displacement, which affects the tracking performance: • Tracking success percentage • Tracking error
Camera handoff	• Handoff success percentage • Handoff error

Hypothetical Calculations of Error Budget Model

Jet Propulsion Laboratory

Terrain	Flat	Small rocks	Large rocks
Approach path	straight	straight	winding
Rover motion step size	20 cm	20 cm	20 cm or 10º
Rover locomotion/navigator ▪ Size change per frame ▪ Pitch/yaw changes	2% at 10m 10% at 2 m –/–	2% at 10 m 10% at 2 m 10º/ –	2% at 10m 10% at 2m 10º/ 10º
VO rover pose ▪ Distance and orientation errors (2%)	0.4 cm / 0.1º	0.4 cm / 0.2º	0.4 cm / 0.3º
Target position error on image plane (stereo triangulation)	1 pixel	1 pixel	1 pixel
Pan/tilt (540:1, 16 CPR) ▪ encoder resolution and backlash ▪ mast calibration accuracy	0.04º	0.04º	0.04º
Overall orientation error for active camera control	0.1º	0.2º	0.3º
Target image displacement between frames ▪ Pancam (17º FOV) ▪ Navcam (45º FOV) ▪ Hazcam (100º FOV) with active gaze	6 pixels 2.3 pixels 1 pixel	12 pixels 4.6 pixels 2 pixels	18 pixels 9.2 pixels 3 pixels
2-D target tracking and camera handoff (tracking percentage and error each step) 1. Pancam for 4 m (from 10 m to 6 m) 2. Handoff from Pancam to Navcam 3. Navcam for 4m (from 6 m to 2 m) 4. Handoff from Navcam to Hazcam 5. Hazcam for 1m (from 2 m to 1 m)	95%; 2 pixels 1 pixel 95%; 3 pixels 1.5 pixels 90%; 2 pixels 1 pixel	90%; 3 pixels 1 pixel 90%; 4 pixels 1.5 pixels 90%; 2.5 pixels 1 pixel	85%; 4 pixels 1 pixel 85%; 5 pixels 1.5 pixels 85%; 3 pixels 1 pixel
Overall single-sol target approach and instrument placement (tracking percentage, pixel error, and placement error)	81%; 3.0 pixels $1\sigma = 2.0$ cm $3\sigma = 6.1$ cm	73%; 3.5 pixels $1\sigma = 2.4$ cm $3\sigma = 7.1$ cm	61%; 4.0 pixels $1\sigma = 2.7$ cm $3\sigma = 8.1$ cm

Mast Calibration

New Mast Calibration Method using Camera Calibration Targets

– Camera calibration targets out on the field
  - More accurate than MER method of using metrology targets on masthead

– We earlier used 7 mast-calibration parameters

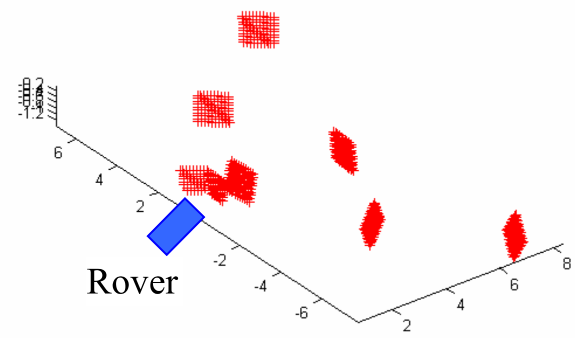
mast t_{xm}	mast t_{ym}	mast t_{zm}	mast θ_{xm}	mast θ_{ym}	pan offset	tilt offset

– We now use 6 mast-calibration parameters

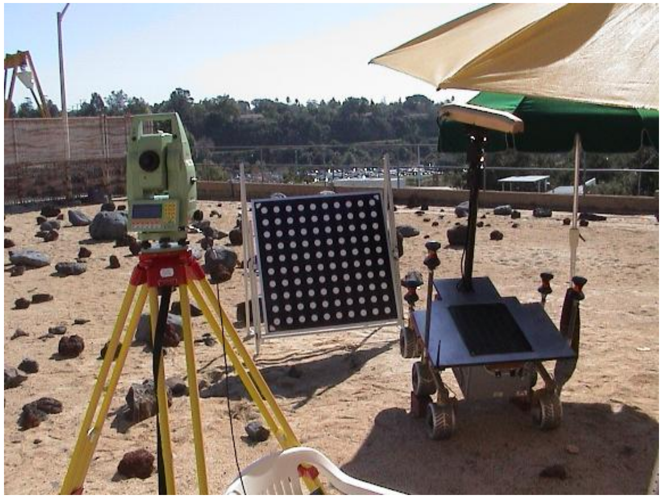
mast t_{xm}	mast t_{ym}	mast t_{zm}	mast θ_{xm}	mast θ_{ym}	mast θ_{zm}

  - pan_offset = tilt_offset = 0

– Mast calibration 2D residual rms errors in pixels
  - 1.13 pixels Navcam = 0.85 mrad = 0.05° accuracy



Calib. target positions (3 pancam, 5 navcam)



Total station, calib. target, and Rocky8 rover

Mast Camera Pointing

Navcam pointing

- point the mast so that the designated target is at the center of the image
- less than 1.3 pixels rms pointing error over 50 target points tested

Camera Aiming Distance	First Camera-Pointing rms pixel error		Second Camera-Pointing rms pixel error	
	Δx	Δy	Δx	Δy
10 m	0.59	1.22	0.53	0.78
6 m	0.74	1.24	0.60	0.84
2 m	1.26	0.93	0.67	0.92

Pancam pointing

- less than 3.3 pixels rms pointing error over 40 target points tested

Camera Aiming Distance	First Camera-Pointing rms pixel error		Second Camera-Pointing rms pixel error	
	Δx	Δy	Δx	Δy
10 m	1.50	3.24	1.17	1.80
6 m	1.63	2.92	1.49	2.02

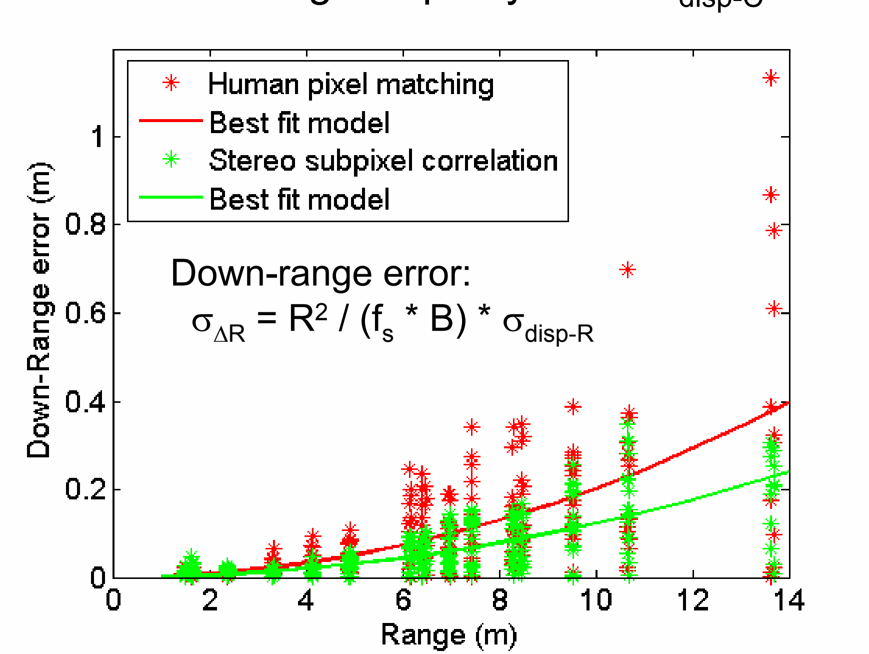
Stereo Range Error Ellipsoids

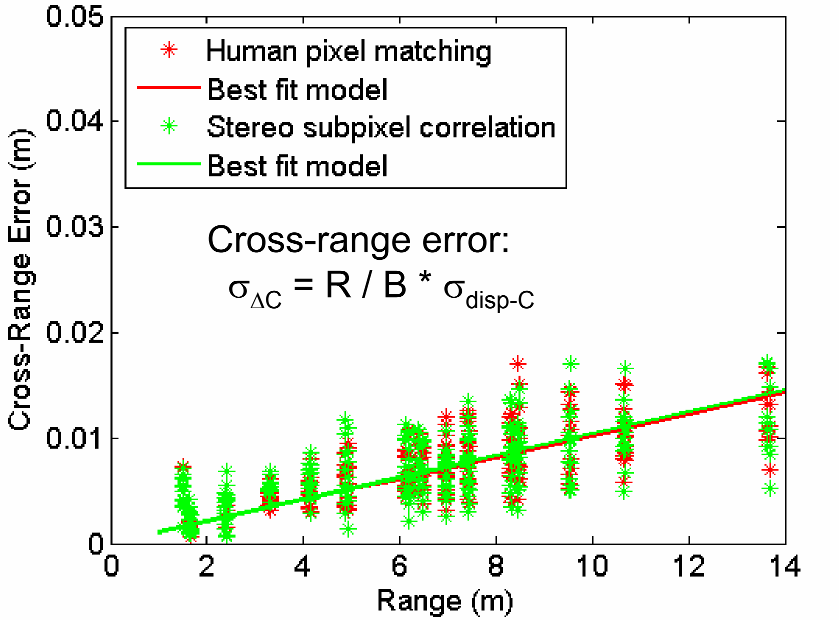
Navcam Stereo Range Error Ellipsoids

– Human integer-pixel matching
  - Down-range disparity error σ_{disp-R} = 0.54 pixels
  - Cross-range disparity error σ_{disp-C} = 1.36 pixels

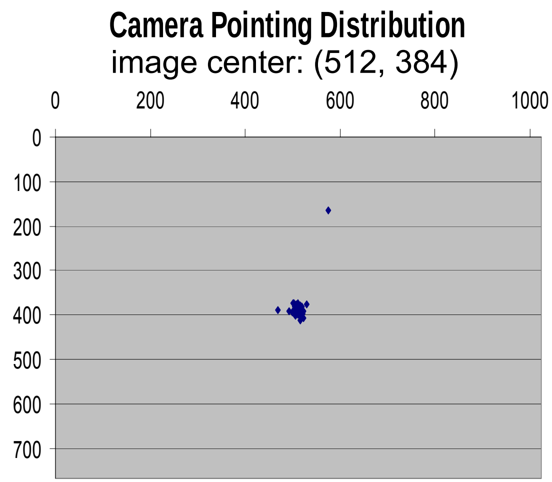
– Stereo sub-pixel correlation matching
  - Down-range disparity error: σ_{disp-R} = 0.32 pixels
  - Cross-range disparity error: σ_{disp-C} = 1.39 pixels

←Experimentally validated using bricks with reflective-tape targets



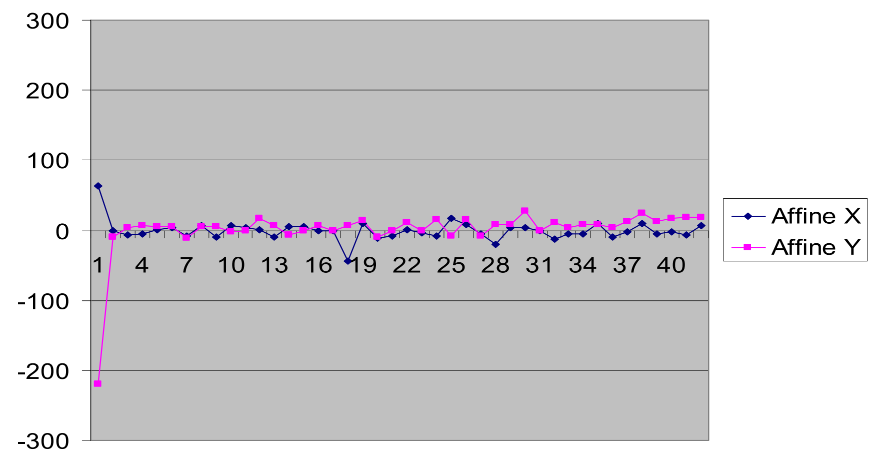


Navcam Tracking over Flat Terrain – Camera Pointing Error



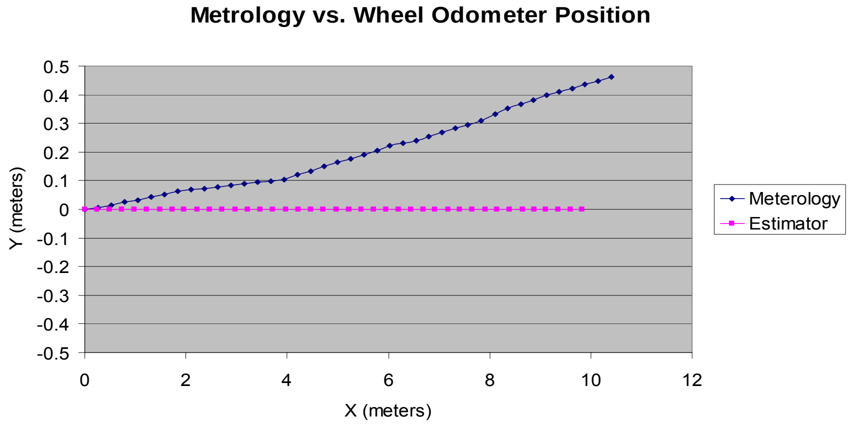
Camera pointing error

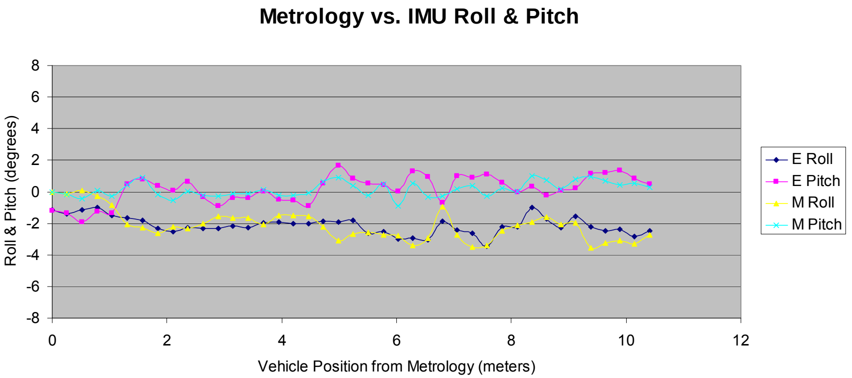
	ΔX	ΔY
σ	10.1 pixels	10.9 pixels
3σ	30.3 pixels	32.6 pixels



Camera pointing error is mainly due to rover pose estimation error; ΔX due to yaw error and ΔY due to pitch error

Navcam Tracking on Flat Terrain – Metrology vs. Estimator

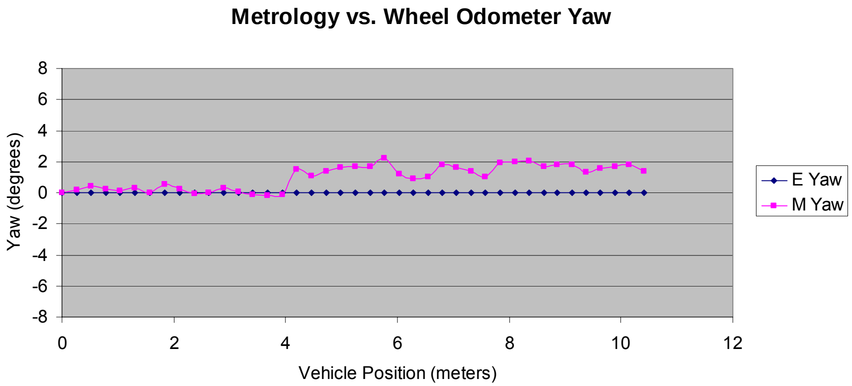




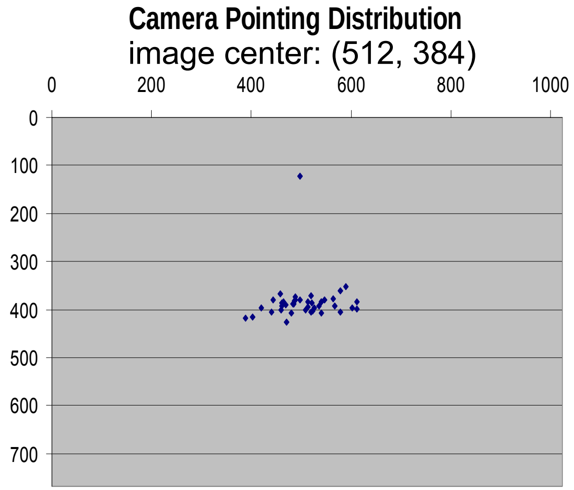
Relative rover pose estimation error

	ΔRoll Error	ΔPitch Error	ΔYaw Error
sigma	0.59 deg	0.62 deg	0.44 deg
3sigma	1.75 deg	1.85 deg	1.32 deg

Camera pointing error depends on the relative rover pose estimation error of each move, not the absolute one.



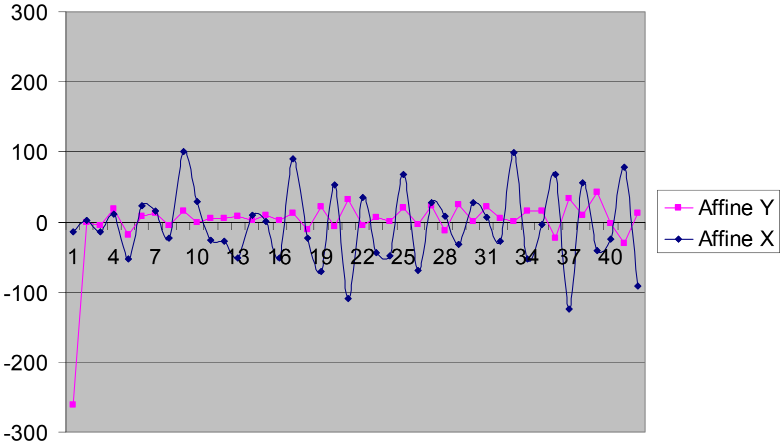
Navcam Tracking over Large Rocks – Camera Pointing Error



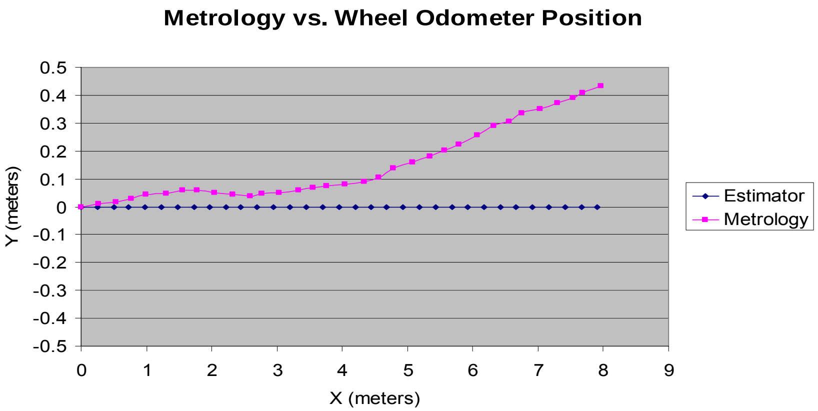
Camera pointing error

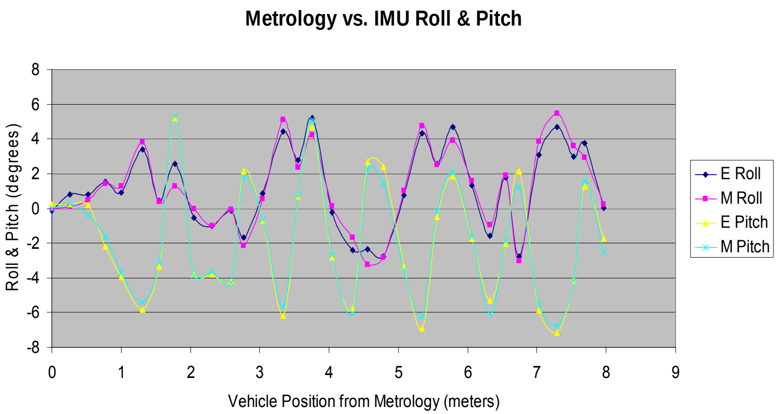
	ΔX	ΔY
σ	54.4 pixels	16.1 pixels
3σ	163.1 pixels	48.3 pixels

Camera pointing error is mainly due to rover pose estimation error; ΔX due to yaw error and ΔY due to pitch error



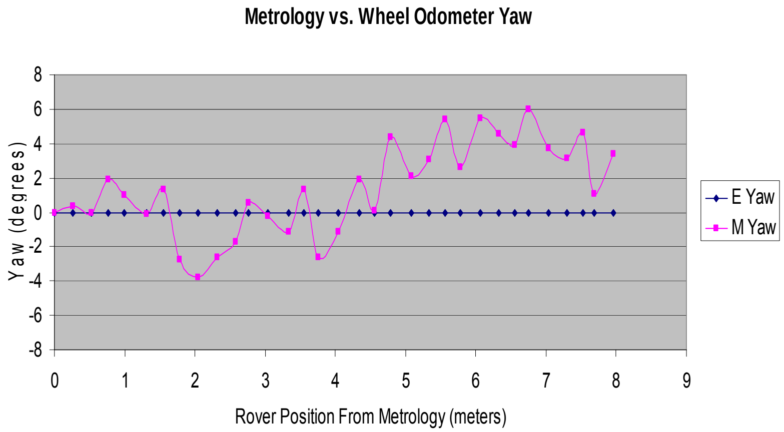
Navcam Tracking over Large Rocks – Metrology vs. Estimator





Relative rover pose estimation error

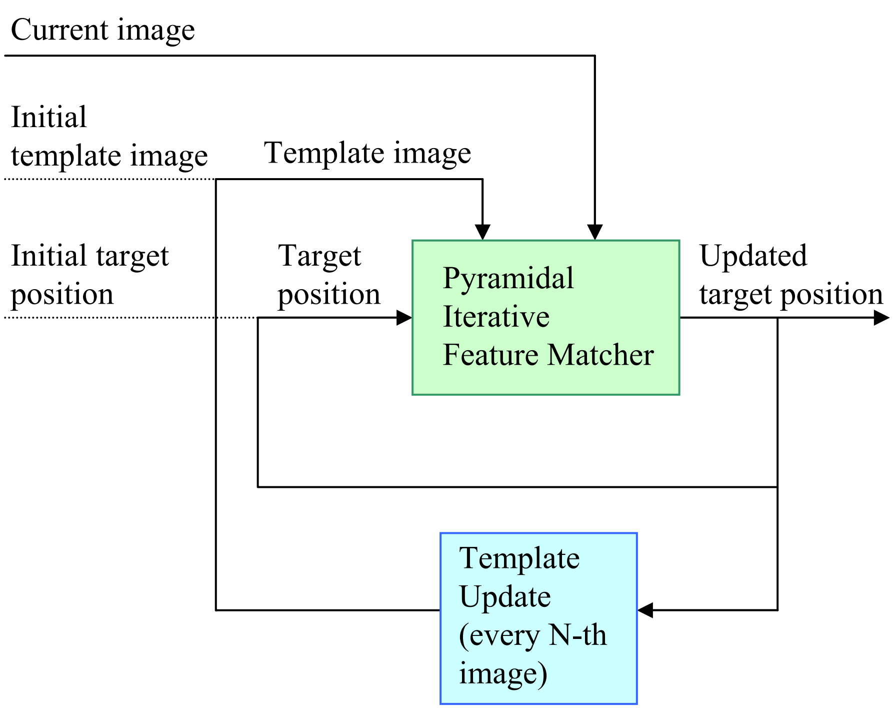
	ΔRoll Error	ΔPitch Error	ΔYaw Error
sigma	0.80 deg	0.58 deg	2.15 deg
3sigma	2.39 deg	1.74 deg	6.48 deg



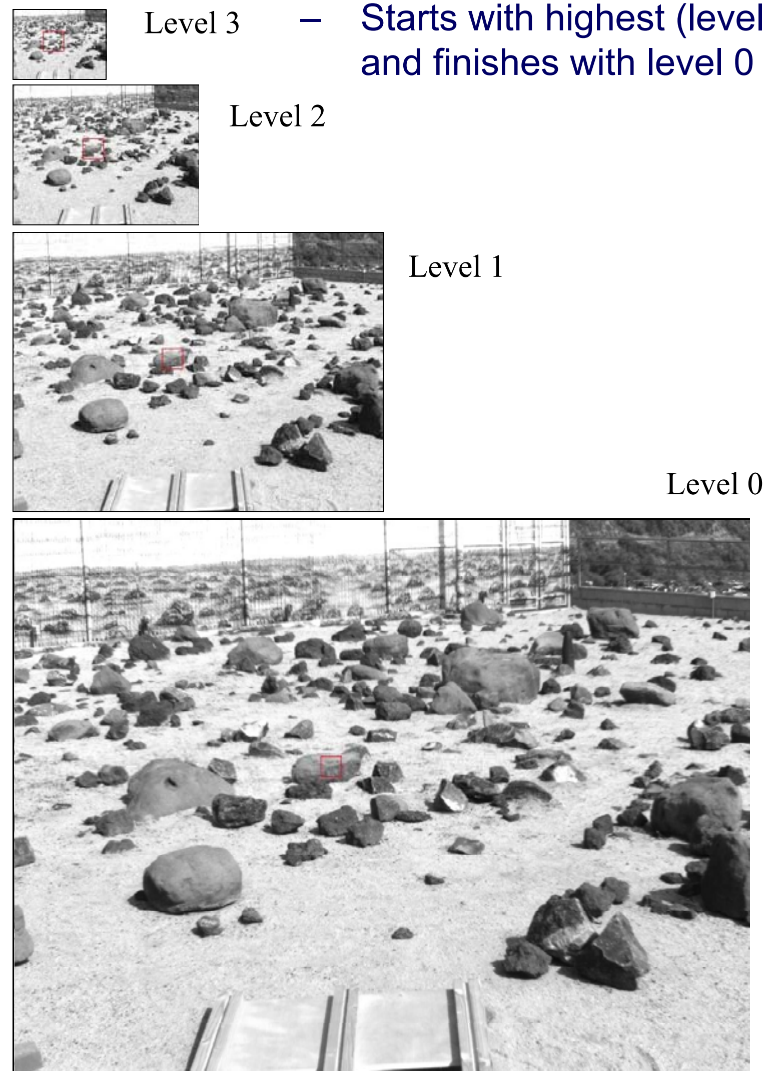
Camera pointing error depends on the relative rover pose estimation error of each move, not the absolute one.

Iterative Pyramidal Affine Matching 2-D Visual Tracker

- Iterative method
  - Successive approximation to the solution



- Pyramidal feature matching
  - Starts with highest (level 3) and finishes with level 0



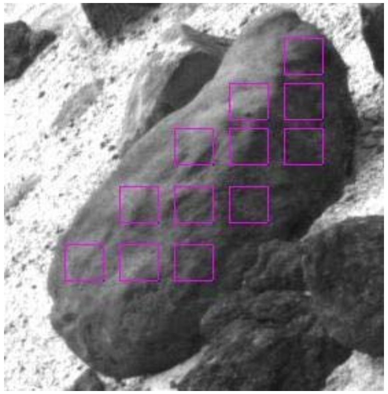
Iterative Pyramidal Affine Matching 2-D Visual Tracker

- Higher pyramid levels handled larger image displacements between images
- Pure translation (more reliable) followed by affine matching (more accurate) was best
- Average tracking performances were 80% up to 100% with 15x15 window for forward, roll, and yaw camera motions
- Low-texture targets on large rocks needed a larger 29x29 window
- Avoid selecting target windows involving occlusions, two separate rocks, cluttered background, shadow change

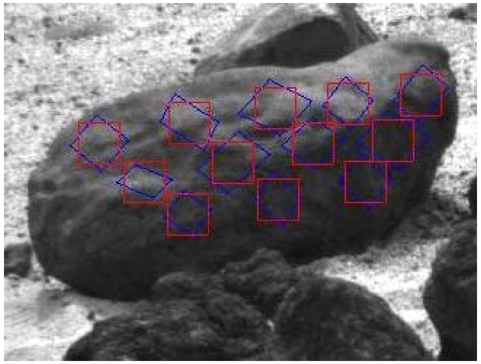
Test run examples with the affine 2-D tracker

Beginning image with 65 initial targets selected

End image after 4-m forward camera motion



Close-up of initial image



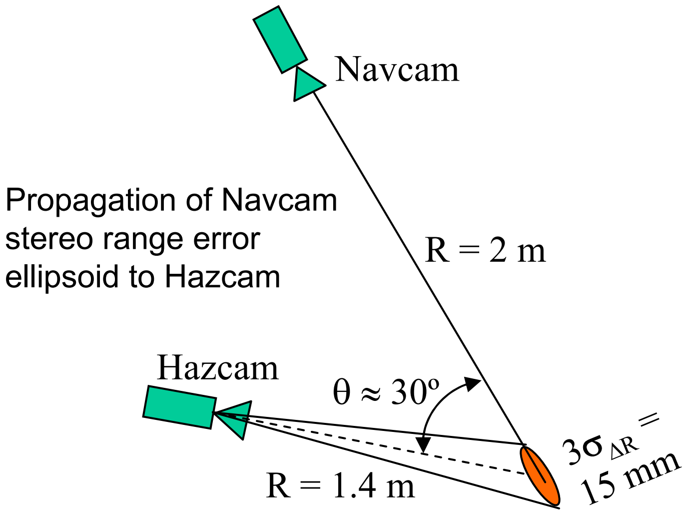
Close-up of end image after 40º camera roll motion

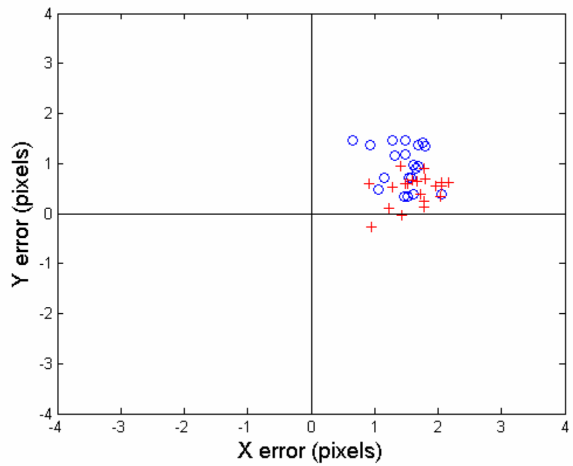
Normalized Cross-Correlation Matching
2-D Visual Tracker

- Problems with the iterative affine matching
  - Iterative search requires good initial seed: tracking range is rather limited to about 10 pixels for higher reliability or 30 pixels for lower reliability
  - Very sensitive to lighting change
- Normalized cross-correlation
  - Brute-force search: entire image search range with very high reliability
  - More robust to lighting change due to normalization
  - Rover motion step size between tracking images is limited due to target image size change allowing less than 5% change in image size
- Normalized cross-correlation with scaling
  - Measure the target distance change using stereo triangulation
  - Scale the target template image according to the target distance change
  - Very reliable enabling a large step size (more than 10% image size change) for rover motion

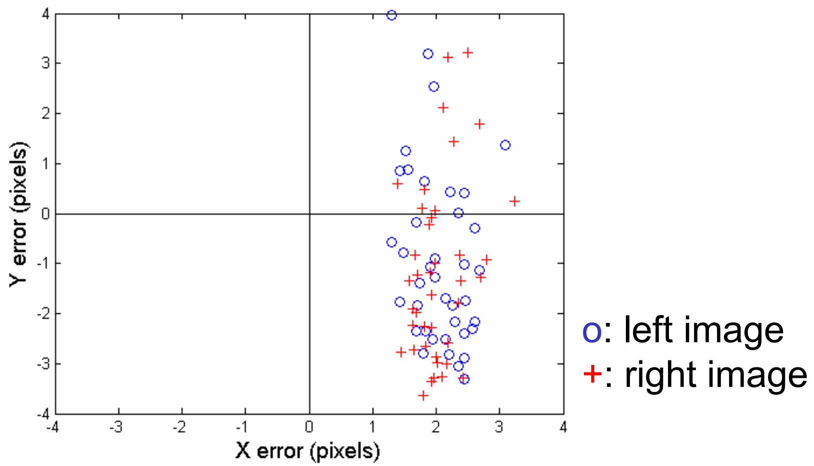
Purely Geometric Camera Handoff

- **Navcam-to-Hazcam handoff error**
  - Up to ~4 pixels with bias of ~2 pixels
  - Bias due to zero-positioning inaccuracy & discrepancy in rover reference frames
  - Larger vertical error spread due to significant down-range error propagation
- **Pancam-to-Navcam handoff error**
  - Up to ~2.5 pixels with bias of ~1.5 pixels





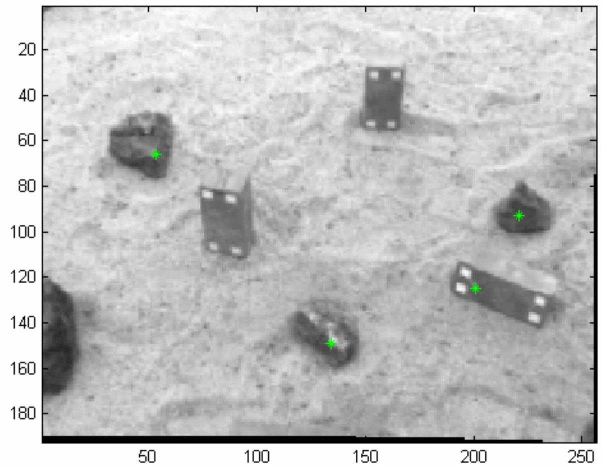
Pancam-to-Navcam handoff error



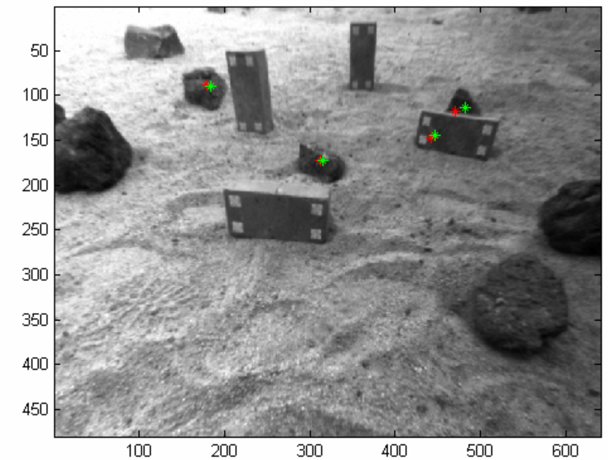
Navcam-to-Hazcam handoff error

Navcam-to-Hazcam Handoff Refinement

Stereo 3-D range based handoff refinement improves the handoff accuracy



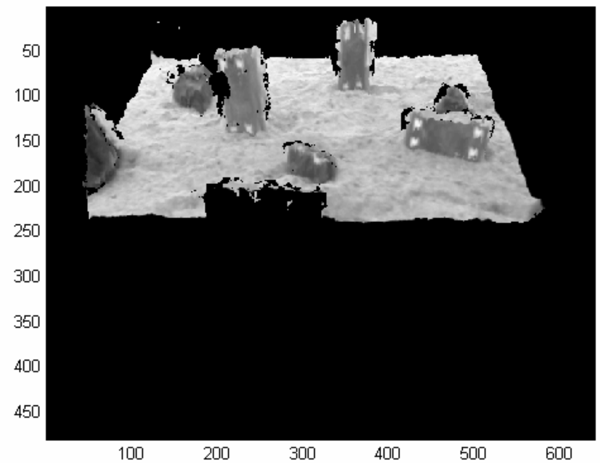
Navcam image



Hazcam image

Red: geometric HO

Green: refinement



1. Construct the hazcam image template by back projection of the navcam image through stereo 3-D range registration

2. Perform normalized cross-correlation between the constructed Hazcam template image and the actual image

Off-line Visual Target Tracker

- Allows multiple runs using a data set collected from real visual tracker
  - only one target tracking per run with real-time visual tracker
- Different target positions
- Different tracking parameters
- Very efficient and essential for tracking performance validation

FY04-05 Publications

– W. S. Kim, R. C. Steinke, R. D. Steele, A. I. Ansar, *Camera Calibration and Stereo Vision Technology Validation Report*, Revision 1, JPL D-27015, Jan. 2004.

– W. S. Kim, R. C. Steinke, R. D. Steele, *2D Target Tracking Technology Validation Report*, JPL D-28523, Apr. 2004.

– W. S. Kim, R. D. Steele, A. I. Ansar, S. Chen, *Test Plan for 2D/3D Visual Target Tracking Validation*, Jul. 2004.

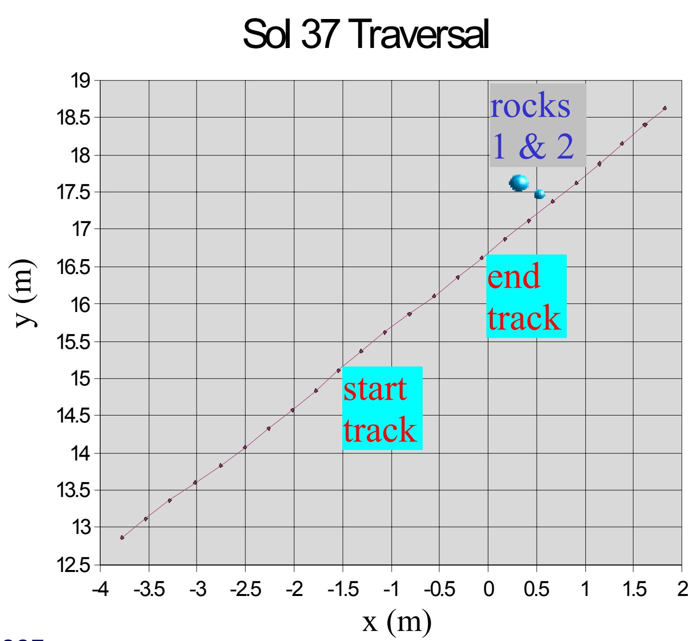
– W. S. Kim, A. I. Ansar, R.D. Steele, “Rover Mast Calibration, Exact Camera Pointing, and Camera Handoff for Visual Target Tracking,” IEEE ICAR’05, Jul. 2005.

– W. S. Kim, A. I. Ansar, R.D. Steele, “Stereo Vision Performance Analysis and an Application to Multi-View Target Registration,” submitted to IEEE SMC’05, Oct. 2005.

MER Hazcam Tracking

Preliminary testing of visual tracking on MER images

- Seven MER Hazcam stereo images of 35-cm step over 2.1 m (CAHVORE model & rover poses given)
- Click images to animate tracking
  - □ : initial seed computed offline by stereo & rover pose
  - □ : after normalized cross correlation (NCC)
  - □ : after affine matching
- Larger rocks and smaller steps desirable for tests

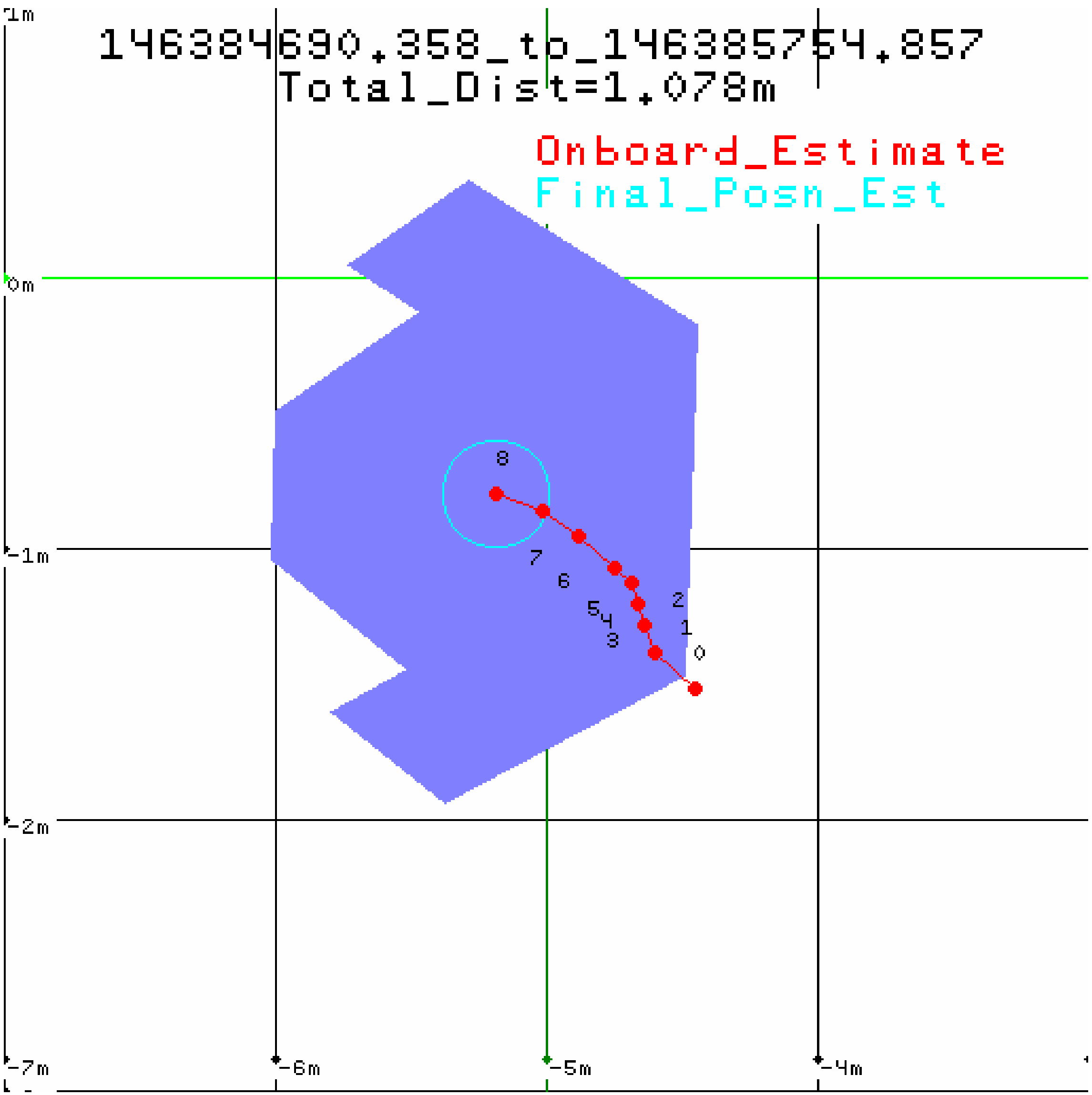


Rock1 Movie

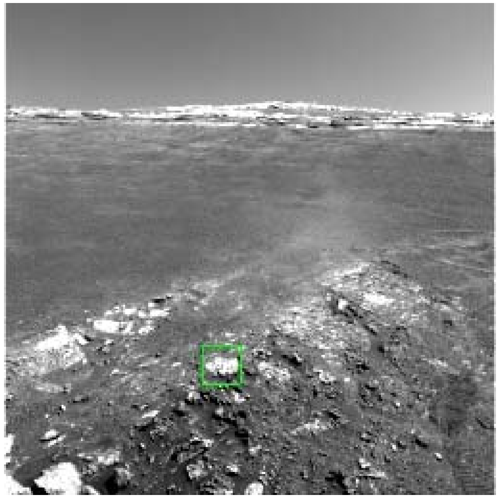
Rock2 Movie

MER Navcam Tracking

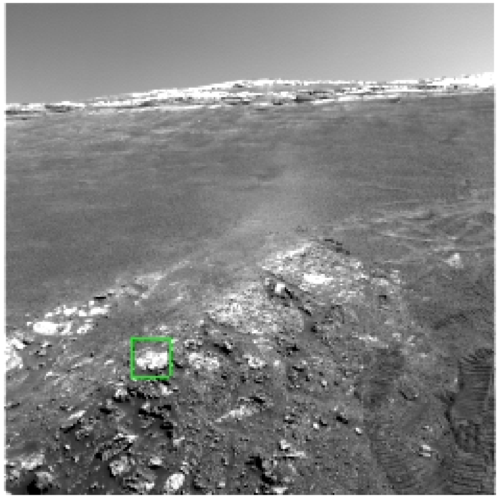
From MER downlink report: rover path



MER Navcam Tracking



#1, movie



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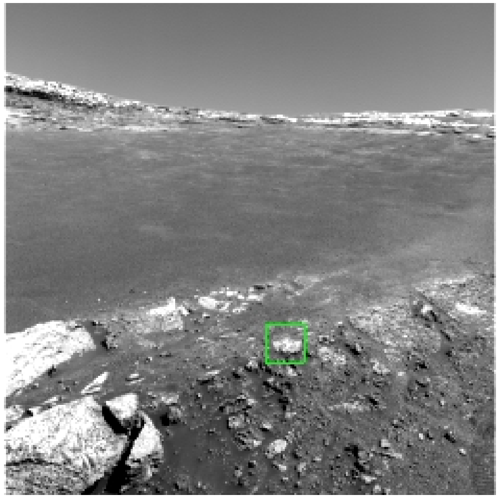
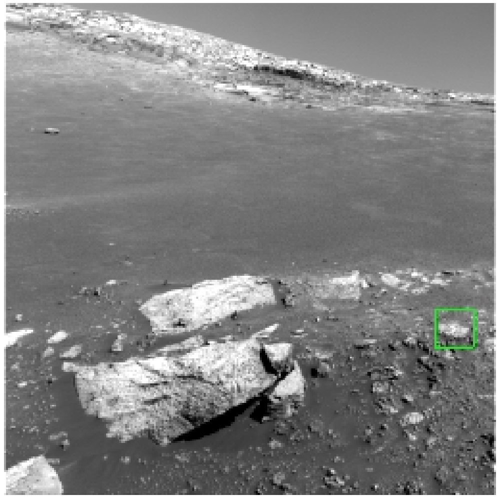


#6



#8